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Aeronomy Laboratory Precipitation Data Products

This document defines the Aeronomy Laboratory (AL) profiler precipitation data that are being made available to the precipitation research community. This document outlines how these data products are determined from the original observations and also defines the format of the output files. This document replaces the original document and refers to version 5 of the software. Improvements and additions to the software are reflected in this document. The main changes are an improved noise determination, detection of saturated data, and more values of the status flags. In addition, two more columns have been added to the output data files.

1. Precipitation Data Products
The precipitation observations made from the Aeronomy Laboratory profilers can be grouped into three different classes: original on-site recorded data, standard precipitation data products, and special profiler derived data products. Each class is outlined below.

Original On-Site Recorded Observations
The original observations are recorded on-site. There are two types of original on-site recorded data: profiler and auxiliary observations. The profiler observations contain the measured Doppler spectra, moments, and pertinent profiler parameters. The auxiliary observations can include surface rain gauge data, disdrometer data, and surface meteorological observations.

The original profiler data will be archived at the Aeronomy Laboratory and used to produce the Standard and Non-Standard Precipitation Data Products described below. The auxiliary observations will be archived at the Aeronomy Laboratory and at other appropriate data archives. The auxiliary data will be archived in their native data format.

Standard Precipitation Data Products
The Standard Precipitation Data Products are profiler derived precipitation data products. For each data record and range gate the equivalent reflectivity factor, the reflectivity-weighted mean Doppler velocity, and the spectral width are determined. The Standard Precipitation Data

Products can be created for any of the Aeronomy Laboratory's radars. These data products are archived at the Aeronomy Laboratory and at other appropriate data archives.

Non-Standard Precipitation Data Products
The Non-Standard Precipitation Data Products are value added products under development and are derived from the original profiler observations. The Non-Standard Precipitation Data Products will be available to collaborators upon special request. Scientists interested in Non-Standard Precipitation Data Products are expected to work in close collaboration with AL scientists. Two examples of Non-Standard Precipitation Data Products under development include multiple peak information and drop size distribution parameter estimates.

2. Determination of Standard Precipitation Data Products

The Standard Precipitation Data Products are derived from the original on-site recorded profiler observations. This section briefly describes how the Standard Precipitation Data Products are derived from the original observations and the format of the output files.

The Standard Precipitation Data Products are derived from the original spectra in the following 12 basic steps. These steps are outlined below and described in detail in the following pages.

1. Extract the moments from the original spectra.
2. Determine the Threshold of Detectability.
3. For each profile, correct the signal-to-noise ratio for enhanced noise.
4. Calculate the equivalent reflectivity factor from the adjusted signal-to-noise ratio.
5. Adjust the equivalent reflectivity by the Time Domain Averaging (TDA) filter response.
6. Define Doppler velocity such that downward motion is negative.
7. Determine the signal headroom of the spectra.
8. Determine a status value for each observation.
9. Write the data products in formatted ASCII files.
10. Modify the ASCII files as required to denote periods of bad data.
11. Name the ASCII files following a convention.
12. Compress hourly ASCII files to reduce file size and to group common files.

1. Extract the moments from the original spectra.
The moments used in the Standard Precipitation Data Products are determined on-site by the real time processing routine. These moments are retrieved from the recorded data using specially developed Profiler Data Access (PDA) routines.

2. Determine the Threshold of Detectability.
The empirically derived Threshold of Detectability determines the minimum signal-to-noise ratio for atmospheric observations. All observations below this threshold are not considered to result from atmospheric scattering processes. The Threshold of Detectability is range independent, but can be converted into reflectivity, which is range dependent. The Threshold of Detectability,

threshold, in log units is defined as:

$$threshold = 10\log\left(\frac{25\sqrt{NFFT - 2.3125 + \dfrac{170}{NPTS}}}{(NPTS)(NFFT)}\right) \quad (1)$$

where NFFT is the number of FFTs averaged to produce the final spectra, and NPTS is the number of points in the spectra. Even if an observation has a signal-to-noise ratio less than the Threshold of Detectability, the output file contains the derived reflectivity, Doppler velocity and spectral width as well as a status flag indicating the observation is below the Threshold of Detectability.

3. For each profile, correct the signal-to-noise ratio for enhanced noise.
For Doppler spectra that span a large fraction of the Nyquist velocity range, there may not be enough spectral points to accurately represent the true noise level. For these broad Doppler spectra, the calculated noise may overestimate the true noise. Thus, the signal-to-noise ratio may be too low, and the subsequent equivalent reflectivity factor may also be too low. Typically, the Nyquist velocity is set to a very large value (~17.5 ms^{-1}) to minimize this effect.

The goal is to replace the elevated noise values with a good estimate of the noise. Since the noise is independent of range, the 8 spectra with the lowest total received power values are used to create a single array containing signal and noise. The Hildebrand and Sekhon method is then used to determine the mean noise level (Hildebrand, Peter H. and R. S. Sekhon, Objective Determination of the Noise Level in Doppler Spectra, Journal of Applied Meterorology, Vol 13, No. 7, pp. 808-811, 1974). This method is based on the statistics of signals and noise, and is the method used by the on-line radar system to determine the noise in each range gate. By applying this method to a larger set of data we get a better noise average, especially in the convective events where there is data in all range gates. The noise at each range is adjusted to produce an adjusted signal-to-noise ratio. This adjusted signal-to-noise ratio is used to calculate the equivalent reflectivity factor.

$$\overline{noise} = N(spectral\ power\ density) \quad (2)$$

The mean noise is determined using a statistical test, N, on selected spectra of the profile. The noise and mean noise can be converted to log units using

$$noise_{\log}(j) = 10\log(noise(j)) \quad (3)$$

$$\overline{noise_{\log}} = 10\log(\overline{noise}) \quad (4)$$

The signal-to-noise ratio, *s2n(j)*, can be expressed in log units by

$$s2n_{\log}(j) = 10\log(s2n(j)) \tag{5}$$

where *s2n(j)* is in linear units expressed for each range gate. The adjusted signal-to-noise ratio, $s2n'_{\log}$, is calculated in log space using

$$s2n'_{\log}(j) = s2n_{\log}(j) + (noise_{\log}(j) - \overline{noise_{\log}}). \tag{6}$$

The adjusted signal-to-noise ratio is calculated in linear space using

$$s2n'(j) = \frac{s2n(j)\, noise(j)}{\overline{noise}}. \tag{7}$$

4. Calculate the equivalent reflectivity factor from the adjusted signal-to-noise ratio.
The liquid water equivalent reflectivity factor is determined from the adjusted signal-to-noise ratio and the range gate distance by

$$z_e(j) = \frac{\mathrm{PRC}}{\mathrm{NPW}^2\,\mathrm{NCI}}\, range(j)^2\; s2n'(j) \tag{8}$$

where PRC is the Profiler Radar Constant, NPW is the pulse width in nanoseconds, NCI is the number of coherent integrations, *range(j)* is the range gate distance in meters, and $s2n'(j)$ is the adjusted signal-to-noise ratio expressed in linear units. The units of the PRC are defined such that the units of $z_e(j)$ are $mm^6\ m^{-3}$. Typically, PRC is a constant and reflects the hardware and software constants for a particular installation. The equivalent reflectivity factor can be expressed in log units by

$$Z_e(j) = 10\log(z_e(j)) \tag{9}$$

and has units of dBZe. All calculations are in reference to liquid water equivalent reflectivity factor. The minimum detectable reflectivity factor is defined using (8) and setting $s2n'(j)$ to the Threshold of Detectability.

By using the signal-to-noise ratio to calculate the reflectivity, variations in the gain of the electronics are removed. Typically these variations are on the order of 1 to 2 dB over the course of a day, and are related to the ambient temperature. These variations are easily observed in the mean noise level.

5. Adjust the equivalent reflectivity by the Time Domain Averaging (TDA) filter response. Coherent integration is a digital filtering process used by profilers. Coherent integration does not increase the signal-to-noise per unit bandwidth in the signal band, but it simply filters out much of the wideband noise. This digital filter is called the Time Domain Averaging (TDA) filter. One side effect of using coherent integration is the decreased power return at frequencies different than zero Doppler shift. This decreased power follows the sinc function with a power response of unity at zero Doppler velocity and the first null located at +/- 2 $v_{Nyquist}$ velocities. The power response for the TDA filter is expressed

$$|\mathrm{H}(v)|^2 = \frac{\sin^2\left(\dfrac{\pi v}{2 v_{Nyquist}}\right)}{NCI^2 \sin^2\left(\dfrac{\pi v}{2 v_{Nyquist} NCI}\right)} \tag{10}$$

where v is the velocity in ms^{-1}, and $v_{Nyquist}$ is the Nyquist velocity in ms^{-1} defined by

$$v_{Nyquist} = \frac{\lambda}{(4\ NCI\ IPP)} \tag{11}$$

where λ is the operating wavelength, and IPP is the inter-pulse period. The calculated equivalent reflectivity factor can be corrected by the inverse of the TDA transfer function and is expressed

$$z_{TDA}(j) = z(j)\ \frac{NCI^2 \sin^2\left(\dfrac{\pi V(j)}{2 v_{Nyquist} NCI}\right)}{\sin^2\left(\dfrac{\pi V(j)}{2 v_{Nyquist}}\right)} \tag{12}$$

where $z(j)$ is the reflectivity at the j^{th} range gate, and $V(j)$ is the reflectivity-weighted mean Doppler velocity at the j^{th} range gate. For simplicity, the subscript "TDA" is omitted in all references to the equivalent reflectivity factor, even though the correction has been applied.

6. Define Doppler velocity such that downward motion is negative.
The Doppler velocity recorded by the profiler is defined as positive motion toward the radar. The sign of the mean reflectivity-weighted Doppler velocity is inverted in the precipitation data products to be consistent with the meteorological convention of downward motion having a negative value.

7. Determine the signal headroom of the spectra.
The Aeronomy Laboratory radars have a large dynamic range (~ 70 dB), but there are occasions when the observed signal does saturate. The maximum observable power value can be calculated based on the analog-to-digital converter word size and knowledge of the detailed algorithms used in the signal processing. For each spectra, the total received power is the sum of all of the points in the power spectra, and can be closely approximated by the sum of the signal and noise powers. The difference between the maximum observable power and the total observed power is defined as the headroom, H:

$$
\begin{aligned}
H(j) &= \frac{4^{(A/D\ bits-1)} * 2^{19} * (3/8) * |\mathrm{H}(V(j))|^2}{s2n(j) * noise(j) * NPTS \ + \ NPTS * noise(j)} \\
H(j)_{dB} &= 10 * \log(H(j))
\end{aligned}
\qquad (13)
$$

Headroom is a measure of how close the signal is to saturating. Using many radar observations and comparing them with co-located disdrometer data, it can be shown that when the headroom is 13 dB or less, the reflectivity is underestimated. Since the total received power is dominated by the signal, the TDA response correction is also appropriate to apply to the calculation of the headroom.

The headroom value of each observation is output with the data. When the headroom is 13.0 dB, or less, the status of the observation is increased by 20. For some purposes, the data is still very useable, but of reduced accuracy due to the saturation. Also, there are occasional bad data in the data stream where the headroom is less than 0. This occurs when the radar system experiences a bad data transfer in some of the digital circuitry, resulting in numbers that are outside the range of the A/D values. These occurrences are given a status of 21 (or 61).

8. Determine a status flag for each observation.
Each observation is assigned a base status flag ranging from 0 to 10. The purpose of the status flag is to classify the observations. A status flag of 0 indicates the observation had a signal-to-noise ratio less than the Threshold of Detectability. A status flag less than 5 indicates a probable clear-air observation and a status flag greater than 5 indicates a probable precipitation observation. The status flags are defined in Table 1.

If the headroom is less than 13 dB, the base status value is increased by 20 to signify possible nonlinear reflectivity values caused by saturation in the radar.

There are rare periods when the radar does not behave in a linear fashion and the reflectivity values are of questionable accuracy. When these periods are identified, the ASCII files are modified by adding 60 to the status flag to indicate questionable calibration of the reflectivities. During these periods, the velocities and widths are still valid, but the signal classification and reflectivities are of reduced accuracy.

Table 1. Status Flag Definitions

Status flag	Description
0, 20, 60, 80	Signal-to-Noise Ratio less than Threshold of Detectability. No atmospheric signal is detected.
21, 81	A bad measurement occurred due to a bad digital data transfer in the radar.
2, 22, 62, 82	Weak Reflectivity with large upward motion. (Z_obs < Z_threshold) & (V_obs > abs(V_threshold)) Dominated by bad data points and interference. Low probability of atmospheric signal.
3, 23, 63, 83	Weak Reflectivity without large downward motion. (Z_obs < Z_threshold) & (abs(V_obs) < abs(V_threshold)) Dominated by clear-air observations.
4, 24, 64, 84	Undefined
5, 25, 65, 85	Undefined
6, 26, 66, 86	Undefined
7, 27, 67, 87	Undefined
8, 28, 68, 88	Strong reflectivity without large downward motion. (Z_obs >= Z_threshold) & (V_obs >= V_threshold)
9, 29, 69, 89	Weak reflectivity with large downward motion. (Z_obs < Z_threshold) & (V_obs < V_threshold)

10, 30, 70, 90	Strong reflectivity with large downward motion. (Z_obs >= Z_threshold) & (V_obs < V_threshold)

Note: V_threshold is a negative value.

As an example of using the Doppler velocity and reflectivity thresholds to identify the precipitation observations, Figure 1 shows the reflectivity versus Doppler velocity scatter plot at 2.14 km above Kapingamarangi during TOGA COARE. The scatter plot shows the grouping of observations around two different clusters. One cluster represents the hydrometeor motions with downward motions ranging from approximately -2 to -10 ms^{-1}. The other cluster represents clear-air motions and the motions in the turbulent boundary layer. There are two constant thresholds drawn in Figure 1, one for reflectivity and the other for Doppler velocity. While the Doppler velocity and reflectivity thresholds shown in the figure don't divide the clusters perfectly, the two thresholds define five sections in this reflectivity-Doppler velocity space. Details of the cluster analysis can be found in Williams, et al. 2000 (Williams, Christopher R., W. L. Ecklund, P. E. Johnston, and K. S. Gage, Cluster Analysis Techniques to Separate Air Motion and Hydrometeors in Vertical Incident Profiler Observations, Journal of Atmospheric and Oceanic Technology, Vol. 17, pp. 949-962, 2000).

Without having a more complete data set available, optimum thresholds to divide the clusters are not possible. We adopt conservative estimates of these thresholds and anticipate improving the separation in the future. Ultimately, the Doppler velocity and reflectivity thresholds are altitude dependent. Currently the Doppler velocity threshold is determined using the rules listed in Table 2. A transition in V_threshold occurs at 3.0 km. This transition level is conservative and it is expected that some turbulent motions will be assigned a status flag of 9 between 3.0 km and the true melting level. The reflectivity threshold, Z_threshold, is independent of altitude in this version and held constant at 20 dBZe.

This software was developed for the TRMM program, and has been applied primarily to tropical data. When applied to non-tropical sites, the classification may become less accurate, especially where the melting layer is lower. In all cases, the reflectivities, velocities, and spectral widths are still valid, so that researchers can develop alternate classifications from the data.

Table 2. V_threshold as a function of Altitude

Altitude	Description
Below the melting level, height <= 3.0 km	V_threshold = -2.0 m/s
Above the melting level, height > 3.0 km	V_threshold = -0.5 m/s

9. Write the data products in formatted ASCII files.

The Standard Precipitation Data Products are written as ASCII files. Each file contains the observations and parameters for one hours worth of observations. The output file is a 2-dimensional matrix. Each row of the matrix is an independent observation, and each column is a different variable or parameter. The contents and format of each column in the output file is described in Table 3. There is one blank space between each formatted column.

10. Modify the ASCII files as required to denote periods of bad data.
When periods of uncertain calibration are identified, a separate piece of software is used to add 60 to the status values of each observation. Only the status values are changed, so this step can be done after the normal processing is completed.

Table 3. Contents and Format of Standard Precipitation Data Products

Column	Mnemonic	Units	Format
1	year	years	I
2	Day-of-year	days	I
3	Hour-of-day	hours (UTC)	I
4	Minute-of-hour	minutes	I
5	Second-of-minute	seconds	I
6	Frequency	MHz	I
7	PRC (Profiler Radar Constant)	N/A	F.2
8	Site Longitude	Degrees East	F.2
9	Site Latitude	Degrees North	F.2
10	Pulse Length	meters	I
11	Range Gate Height	meters above Mean Sea Level (MSL) (center of range gate)	I
12	Minimum Detectable Reflectivity	dBZe	F.2
13	Reflectivity	dBZe	F.2
14	Doppler Velocity	ms^{-1}	F.2
15	Spectral Width	ms^{-1}	F.2
16	Status Flag	integer	I2

17	Mean noise level of profile	dB (in POP relative units	F.2
18	Headroom	dB	F.2

A sample of the Standard Precipitation Product output file from one time and the first 30 range gates is shown below:

```
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 119 -45.60 17.16 -6.07 5.18 9 21.11 29.30
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 179 -41.93 23.22 -6.33 2.45 10 21.11 26.92
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 239 -39.35 23.47 -6.99 2.42 10 21.11 29.24
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 299 -37.37 23.69 -7.20 2.32 10 21.11 31.01
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 359 -35.76 23.51 -7.25 2.31 10 21.11 32.80
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 419 -34.40 23.87 -7.33 2.25 10 21.11 33.80
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 479 -33.22 23.76 -7.38 2.29 10 21.11 35.08
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 539 -32.19 23.39 -7.31 2.40 10 21.11 36.48
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 599 -31.26 23.48 -7.33 2.43 10 21.11 37.32
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 659 -30.43 23.45 -7.28 2.16 10 21.11 38.19
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 719 -29.66 22.80 -7.24 2.42 10 21.11 39.60
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 779 -28.96 22.63 -7.24 2.42 10 21.11 40.47
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 839 -28.31 22.38 -7.15 2.19 10 21.11 41.36
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 899 -27.71 22.71 -7.16 2.08 10 21.11 41.64
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 959 -27.15 21.92 -7.24 2.20 10 21.11 42.99
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1019 -26.62 21.35 -7.13 2.32 10 21.11 44.09
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1079 -26.12 21.60 -7.12 2.25 10 21.11 44.33
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1139 -25.65 20.94 -7.16 2.33 10 21.11 45.46
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1199 -25.20 21.05 -7.26 2.30 10 21.11 45.80
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1259 -24.77 21.18 -7.45 2.30 10 21.11 46.10
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1319 -24.37 20.92 -7.46 2.39 10 21.11 46.76
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1379 -23.98 21.04 -7.61 2.37 10 21.11 47.03
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1439 -23.61 21.42 -7.68 2.28 10 21.11 47.02
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1499 -23.25 21.44 -7.64 2.26 10 21.11 47.36
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1559 -22.91 21.34 -7.63 2.20 10 21.11 47.80
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1619 -22.58 21.24 -7.56 2.28 10 21.11 48.23
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1679 -22.26 21.10 -7.59 2.32 10 21.11 48.68
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1739 -21.96 20.87 -7.52 2.31 10 21.11 49.21
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1799 -21.66 21.00 -7.56 2.32 10 21.11 49.38
2001 253 15 00 10 2835 0.48151 -102.4656 17.2330 60 1859 -21.38 20.91 -7.55 2.29 10 21.11 49.75
```

11. Name the ASCII files following a convention.

The output ASCII file is named following the convention:

sss_ffff_yyyy_ddd_hh_vx.txt

where the relationship between the mnemonics and the contents are listed in Table 4.

Table 4. Naming Convention Decoding Matrix

Designator	Meaning	Options	Description
sss	Site Name	tex flo bra kwa nhz	Houston, Texas Triple N Ranch, Florida Ji-Parana, Brazil Kwajalein, Marshall Islands RV New Horizon

ffff	Frequency	0915 2835	915 MHz profiler 2835 MHz profiler
yyyy	Year	1998-2002	Year
ddd	Day-of-year	001 to 366	Day-of-year
hh	Hour of day	00 to 23	Hour of day (UTC)
vx	Version	v1 v2 v5	Version 1. Released: 30 June 1998 Version 2. Released: 16 January 2001 Added ability to use pulse-coded data Version 5. Released: 11 February 2002 Added noise level and headroom to outputs. Added more status flags.
.txt	ASCII file	.txt	File Extension

Note that all letters are lower case. Here are two examples of the file naming convention:

<u>File Name</u>	<u>Translation</u>
tex_0915_1998_098_17_v1.txt	Houston, Texas; 915 MHz profiler; year 1998; day-of-year 98; hour-of-day 17; Version 1; ASCII format.
Flo_2835_1998_240_04_v1.txt	Triple N Ranch, Florida; 2835 MHz profiler; year 1998; day-of-year 240; hour-of-day 4; Version 1; ASCII format.

12. Compress hourly ASCII files to reduce file size and to group common files.
The ASCII files for each day consists of up to 24 hourly files. To save disk space and to organize the files, these ASCII files are 'zipped' using the PC 'zip' command.

The naming convention of the daily zip file is:

sss_ffff_yyyy_ddd_vx.zip

where the mnemonics are the same as listed in Table 4, and the extension '.zip' indicates a zip file.

Here are two examples of the zipped file naming convention:

<u>File name</u>	<u>Translation</u>
tex_0915_1998_098_v1.zip	Houston, Texas; 915 MHz profiler; year 1998; day-of-year 98; Version 1; zip format. Contents are zipped hourly files.
flo_2835_1998_240_v1.zip	Triple N Ranch, Florida; 2835 MHz profiler; year 1998; day-of-year 240; Version 1; zip format. Contents are zipped hourly files.

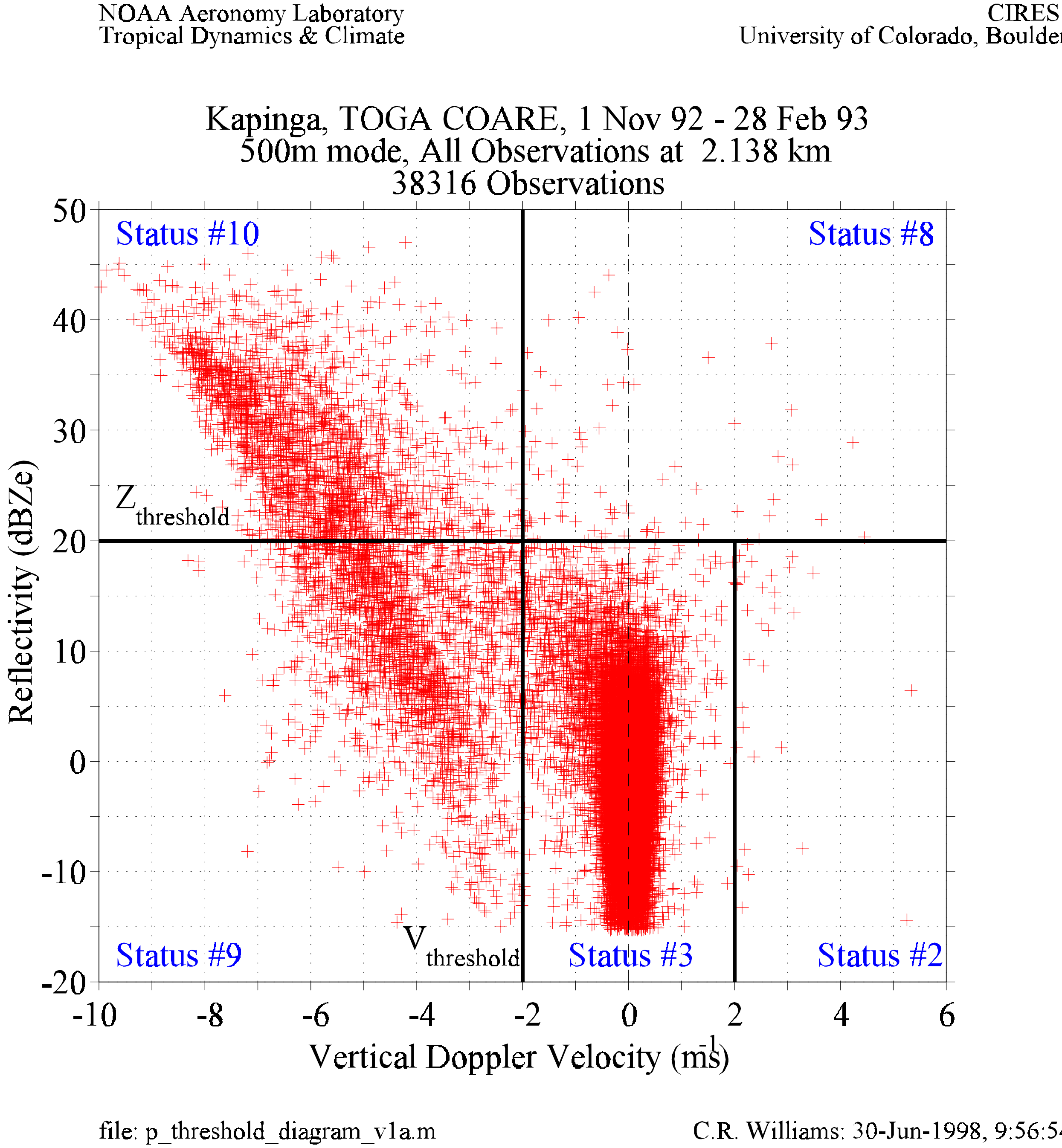

Figure 1. Scatter plot 915 MHz profiler observed vertical Doppler velocity versus equivalent reflectivity at 2.138 km above Kapingamarangi during TOGA COARE (1 Nov 92 through 28 Feb 93). The velocity and reflectivity thresholds are drawn. The status flags for #2, #3, #8, #9, and #10 are also indicated.